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SUMMARY

This paper presents an algorithm which can be used for scheduling arrival air traffic in an Air Route Traffic Control Center (ARTCC, or "Center") entering a Terminal Radar Approach Control (TRACON) Facility. The algorithm aids a Traffic Management Coordinator (TMC) in deciding how to restrict traffic while the traffic expected to arrive in the TRACON exceeds the TRACON capacity. The restrictions employed fall under the category of Miles-in-Trail (MinT)—one of two principal traffic separation techniques used in scheduling arrival traffic. The algorithm calculates aircraft separations for each stream of aircraft destined to the TRACON. The calculations depend upon TRACON characteristics, TMC preferences, and other parameters adapted to the specific needs of scheduling traffic in a Center. Some preliminary results of traffic simulations scheduled by this algorithm are presented, and conclusions are drawn as to the effectiveness of using this algorithm in different traffic scenarios.

INTRODUCTION

The Federal Aviation Administration (FAA) is in the midst of upgrading air traffic control facilities around the nation, some of which date back to the 1950s. Although air traffic controllers continue to be the traffic management decision makers, both the FAA and the National Aeronautics and Space Administration (NASA) are developing automation tools for these facilities to assist the controllers in the decision process. One such tool is the Center-TRACON Automation System (CTAS) (ref. 5), which, among other things, can be used to assist a Traffic Management Coordinator (TMC) in scheduling arrival traffic in the

Air Route Traffic Control Center (ARTCC, or "Center")¹ to a Terminal Radar Approach Control Facility (TRACON).²

CTAS uses time-based scheduling (ref. 2) to schedule aircraft to cross a geometric location at a precise time, which requires forecasting aircraft four-dimensional (4-D) trajectories (ref. 1). CTAS uses aircraft performance characteristics, airspace models, real-time radar tracking, and weather data to develop optimal 4-D trajectories for all aircraft in a Center destined to a TRACON within the Center. These trajectories are used to estimate when an aircraft arrives at a particular 4-D target, such as a feeder fix into a TRACON. These estimates are referred to as estimated times of arrival (ETA) to a feeder fix. Although time based scheduling is considered to be an "optimal" traffic management technique (refs. 3 and 4), only two out of twenty Centers in the United States use time-based scheduling as the primary traffic management technique. The primary traffic management technique used by most Centers in the United States is Miles-in-Trail (MinT).

MinT is a technique used for lining up traffic in trail and selecting how many miles should be placed between aircraft in the trail. We refer to these trails as streams. A Center has several streams of traffic feeding a TRACON at feeder fixes (fig. 1). Center scheduling requires predicting what effect these streams of traffic have on the TRACON over a scheduling time range. That is, appropriate separation requirements must be placed on each stream so that over a scheduling time range the correct number of aircraft enter the TRACON from all the streams. The time range may be between 15 and 30 minutes. Over this time range, if too many aircraft are estimated to arrive at their feeder fixes, the TMC spreads out and delays the traffic so that an acceptable number of aircraft arrive at the feeder fixes.

¹U.S. airspace is divided into 20 Centers.

²TRACON spans a 30- to 50-n.mi. radius from an airport.

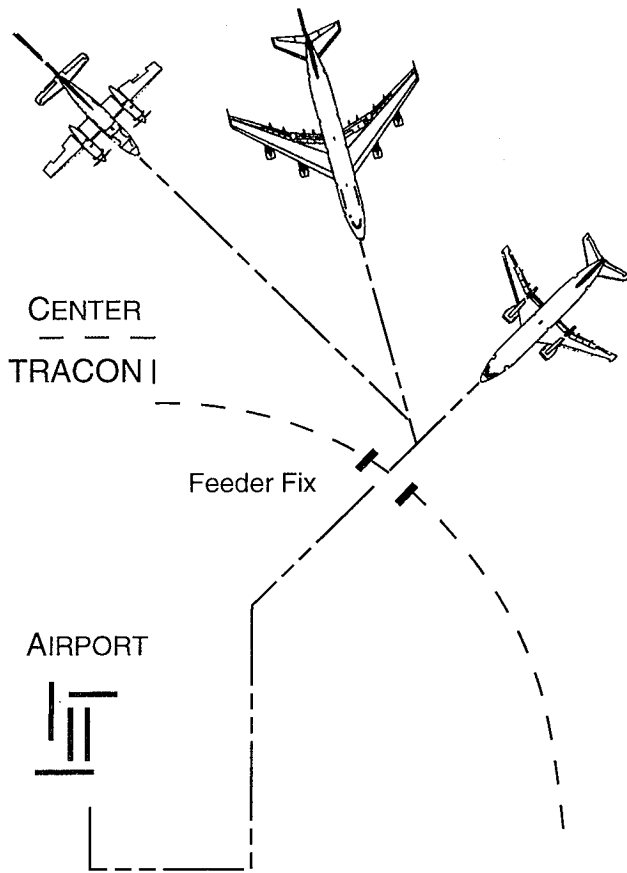


Figure 1. Center TRACON boundary.

To do this, the TMC imposes different MinT restrictions on each stream, which means that all aircraft in a stream must be separated by at least the MinT value.

The algorithm presented in this paper addresses issues associated with adapting the time-based scheduling provided by CTAS to provide MinT restrictions. MinT is an important element of CTAS, for the infrastructure throughout the country and the experience in using MinT restrictions in the U.S. can make it easier to incorporate MinT automation aids than time-based scheduling aids, at least in the nascence of modern air traffic control. The remainder of the paper is organized to provide a brief description of the air traffic problem for which the algorithm has been designed to solve, to describe a general solution technique for this problem, to describe methods for identifying traffic characteristics which are relevant to the scheduling process, and to provide a detailed description of the algorithm, and simulation results based on the algorithm.

THE PROBLEM

Part of the process of traffic management is determining when to alter the course of the traffic flow. This paper addresses the problem of a "rush" and how to distribute traffic such that one avoids a "traffic jam." There is a rush when the traffic expected to arrive at a TRACON over a scheduling time range, as predicted by traffic ETAs, exceeds that which is permitted by the TRACON constraints. During a rush, the TMC must issue restrictions at enough streams to reduce the traffic. TMCs across the nation use different techniques to achieve this traffic reduction. TMCs at one Center could try to distribute aircraft delays in a manner which preserves the projected aircraft arrival order, referred to as "first come first serve." This can result in restrictions on every stream. Other Centers apply most of the restrictions on streams with light traffic to reduce the workload that would be incurred by restrictions on "heavy" streams and to increase the traffic throughput.

Automating the scheduling process is difficult, not only because the automation must be able to use either of these restriction techniques to be adaptable to the particular techniques used in a Center, but also because there are many combinations of stream restrictions which can reduce the traffic to the proper number of aircraft. The scheduling tool must select only a few of the many solutions to present to the TMC who could use one of the solutions, modify a solution, or modify the constraints used by the scheduler to develop a new solution.

SOLUTION TECHNIQUE

The algorithm attempts to distribute delay in an equitable fashion, but restricts lighter traffic streams before restricting streams with heavy traffic, thus reducing total controller workload. The algorithm also has constraints which the TMC can modify, which include: the time range, $t_f - t_0$, over which to derive a solution; the maximum acceptable number of aircraft, N_{acc} , permitted to enter the TRACON sometime during this time range; the minimum number of aircraft in a stream which make the stream a candidate for restrictions; the maximum MinT restriction to be used by the algorithm; and prescribed MinT values on as many

streams as the TMC chooses. The scheduling objective is to determine how many miles to place between aircraft on streams which have not had their restriction prescribed by the TMC. These restrictions must result in an acceptable amount of traffic entering the TRACON.

The main objective of this algorithm is to attempt to distribute aircraft delays equitably, with a constraint to impose restrictions on streams with light traffic before imposing restrictions on streams with heavy traffic. Thus, the algorithm tries to reduce total Center controller workload, while maintaining a sense of balance in delay distribution. "Equitable" means placing restrictions which preserve the ratio of the stream's unrestricted to total unrestricted traffic. After placing restrictions for all streams, a refinement algorithm is used to reduce some of the traffic restrictions, starting with streams which are the most difficult to restrict. Details of this algorithm are presented in the next section.

Equitable Delay Distribution

For each stream, j , determine the maximum number of aircraft, N_j^{max} , that can be scheduled to enter the TRACON over the scheduling time range, while adhering to FAA minimum separation constraints for the Center, and while adhering to the TMC's commanded separations. Note that this count may differ from a count based on current ETAs to the feeder fix, which are calculated as described in the introduction, because a count based on ETAs can violate FAA regulations for minimum separation between aircraft in the Center.

The scheduled times of arrival (STA) to the feeder fixes for all aircraft are calculated as follows. First sequence the traffic in a stream by ETAs. Label these $ETA_1 \dots ETA_n$, where ETA_1 is the time at which the first aircraft, ac_1 , is expected to arrive at the feeder fix for this stream. Schedule ac_1 to arrive at its ETA,

$$STA_1 = ETA_1 \quad (1)$$

Now determine the flight time ΔT_2 for the second aircraft, ac_2 , to fly *min* nautical miles, where *min* is the minimum required distance separating ac_2 from ac_1 when ac_1 crosses the feeder fix for this stream. That is to say, when ac_1 crosses the destination, ac_2 should be no closer than *min* nautical miles to the destination. *min* is equal to 5 nautical miles or the value set

by the TMC. The flight time information, ΔT_2 , is determined by CTAS trajectory routines as a function of aircraft flight characteristics, weather, air carrier procedures and more (ref. 1). Adding ΔT_2 to STA_1 yields the earliest STA for ac_2 .

$$STA_2^{min} = STA_1 + \Delta T_2 \quad (2)$$

If STA_2^{min} is later than ETA_2 , schedule ac_2 to STA_2^{min} . Otherwise, schedule ac_2 to arrive at ETA_2 . This is done because the algorithm under consideration does not "speed up" an aircraft to get in ahead of the current estimated time of arrival. The algorithm can easily be modified to allow aircraft to speed up, especially to "front load" the TRACON in a rush. However, for this discussion, assume that the ETAs are the preferred arrival times for the aircraft. Proceed with this logic until STAs have been assigned to all the aircraft in a stream.

$$STA_i^{min} \equiv STA_{i-1} + \Delta T_i \quad (3)$$

$$STA_i = \begin{cases} STA_i^{min}, & \text{if } STA_i^{min} > ETA_i; \\ ETA_i, & \text{otherwise} \end{cases} \quad (4)$$

Now determine N_j^{max} , the maximum aircraft count which could be scheduled to enter the TRACON from stream j between t_0 and t_f . This is accomplished by counting the number of aircraft scheduled between t_0 and t_f .

$$N_j^{max} = \sum_{i=1}^{n_j} \begin{cases} 1, & \text{if } t_0 \leq STA_i \leq t_f; \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

The maximum aircraft count predicted to enter the TRACON over this scheduling region is just the sum of the individual maximum counts for each stream,

$$N_{max} = \sum_{j=1}^S N_j^{max} \quad (6)$$

where S is the number of streams being controlled. If N_{max} is equal to or below the accepted count for this range, N_{acc} , the schedule is acceptable. Otherwise, proceed as follows.

Determine how many aircraft, N_{TMC} , have been scheduled by the TMC between t_0 and t_f .

$$N_{TMC} = \sum_{j=1}^S \begin{cases} N_j^{max}, & \text{if MinT set by TMC} \\ 0, & \text{otherwise} \end{cases} \quad (7)$$

Remove this count from the total count N_{max} , to get the unrestricted traffic count over the streams for which the scheduler is to derive MinT values. Call this N_{un} .

$$N_{un} = N_{max} - N_{TMC} \quad (8)$$

The scheduler derives MinT values to reduce N_{un} such that the scheduled count into the TRACON between t_0 and t_f falls below or is equivalent to the acceptance count, N_{acc} . The scheduler derives MinT values for the traffic affected by the scheduler, and does not override restrictions manually imposed by the TMC. So N_{TMC} can be removed from N_{acc} to get the desired count, the scheduler attempts to provide

$$N_{des} = N_{acc} - N_{TMC} \quad (9)$$

Many techniques could be used to reduce the traffic to the desired count. One technique is to attempt to distribute the traffic reduction evenly across all streams. This may be done by finding a stream's ratio of maximum count to total unrestricted count

$$R_j = \frac{N_j^{max}}{N_{un}} \quad (10)$$

and multiplying this ratio by N_{des} to get this stream's desired count

$$N_j^{des} = R_j N_{des} \quad (11)$$

Of course, the likelihood that this results in an integral number of aircraft is very low. Furthermore, the exact MinT needed to separate traffic out to achieve this count is likely to be unacceptable as a target value—MinT commands are issued in increments of 5 nautical miles. The exact value is unlikely to meet this requirement. Although these limitations can bring to question the usefulness of this distribution function, it will be shown that it can be used to form a fairly reasonable solution.

REALISTIC SOLUTION

With only slight modifications, the delay distribution logic presented earlier can be altered to provide a plausible solution to the traffic distribution problem. The stream ratios are determined as described earlier. A method for measuring a stream's traffic density is also developed. After determining the traffic density of every stream, the streams are enumerated based on density. Greater density traffic requires more effort to

achieve a commanded separation between aircraft than does lower density traffic. As such, if there were a choice in where to place a higher restriction, a low density stream is chosen to avoid unnecessary work load on a controller of a more dense stream. Having enumerated the streams, the desired traffic count for each stream is calculated using equation (11), which in turn is used to determine a valid separation. Typically a valid separation is an integral number of 5 nautical miles. This value, $MinT_j$, is most likely to cause the traffic count, N_j , to be less than N_j^{des} , resulting in traffic loss. This traffic loss is recorded and summed for all streams to measure the over-restrictions placed on the traffic. After a preliminary schedule has been created using this logic, a refinement algorithm reduces separation constraints, if such reductions result in a traffic count closer to but not exceeding the desired count.

TRAFFIC IDENTIFICATION

The decision of which streams to place restrictions on is based on an evaluation of the current traffic patterns in each stream. These patterns must be quantified for the scheduler to distinguish between streams of varying traffic patterns. One parameter useful for evaluating traffic is cumulative delay. Although useful for post-evaluation of a schedule, this does not help determine a schedule, for delay depends on the schedule. The following parameters can quantify traffic patterns based solely on ETAs, and are used to decide which streams should be restricted first in the scheduling process. Figure 2 shows three traffic patterns which could evolve over a scheduling time range t_0 to t_f . Each vertical line in the figure represents an aircraft in a stream. In particular, each line represents the time at which the aircraft is estimated to arrive at the feeder fix for the stream. We use this figure to describe the advantages and disadvantages of two traffic identifiers, ETA density and ETA integral developed for MinT scheduling.

ETA Density

After enumerating the aircraft in a stream of traffic by their ETAs, calculate the ETA density as the sum of the squares of the differences in aircraft ETAs for the stream.

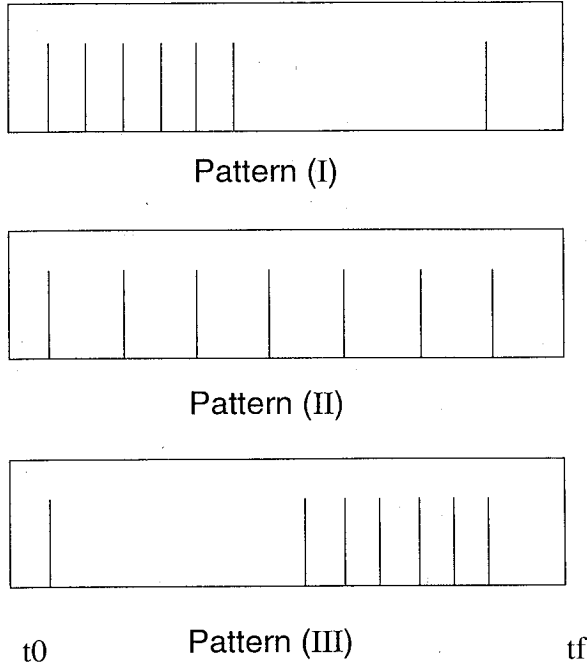


Figure 2. Three arrival time traffic patterns.

$$\rho_j = \tau + (n_j - 1)^2 \sum_{i=2}^{n_j} (ETA_i - ETA_{i-1})^2 \quad (12)$$

$$\tau \equiv (n_j - 1)^2 \left[(ETA_1 - t_0)^2 + (t_f - ETA_{n_j})^2 \right]$$

Take the sum of the squares rather than just the sum of the differences for the following reason: the sum of the differences in ETAs is the same for all three traffic patterns (fig. 3). Therefore, it could not be used to differentiate between the traffic patterns. Equation (12) would yield different values, which are the same for patterns (I) and (III), and lower for pattern (II). This is useful in that it can serve as an indicator that it requires greater work load to separate traffic in patterns (I) and (III) than it would for (II).

ETA Integral

Another traffic measurement technique is the ETA integral. The integral is determined by the following:

$$ETA_0 \equiv t_0$$

$$I_j = n_j(t_f - ETA_{n_j}) + \sum_{i=1}^{n_j} (ETA_i - ETA_{i-1}) * i \quad (13)$$

This gives separate measures for each of the patterns in figure 2. The integral for (I) is greater than that of (II) which is greater than (III). We see that the ETA integral places greater weight on aircraft arriving early. This can indicate that it is more difficult to separate traffic closer to than further from a destination. Equation (13) is used for deriving solutions for the traffic restrictions to be described next, but is subject to further simulations with evaluation from TMCs expected to shed light on its effectiveness. Equation (12) can serve as a better measure of workload for different traffic patterns.

Arrival Rate Graph

A traffic identifier related to the ETA integral is the ETA rate graph. An arrival rate graph is a series of curves, where each curve is associated with a different stream. Each curve is constructed by plotting an aircraft's arrival order in the stream versus the aircraft's projected arrival time at the stream destination, a feeder fix, for all aircraft in a stream. The ETA integral for a stream is approximately equal to the area between the stream's arrival rate curve and the time of arrival axis. Figures 3 and 4 depict ETA and STA rate graphs, respectively.

We note from figure 3 that there are nine aircraft projected to fly in the *TOMSN_A* stream over the next 6000 seconds. Scheduling restrictions have been imposed between 0 and 2400 seconds. A vertical line at 2400 seconds represents the time at which restrictions end. The other two straight lines in figure 3 depict

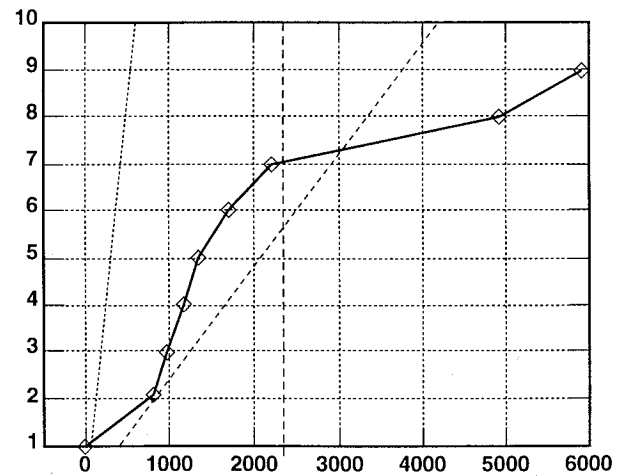


Figure 3. ETA arrival rate graph.

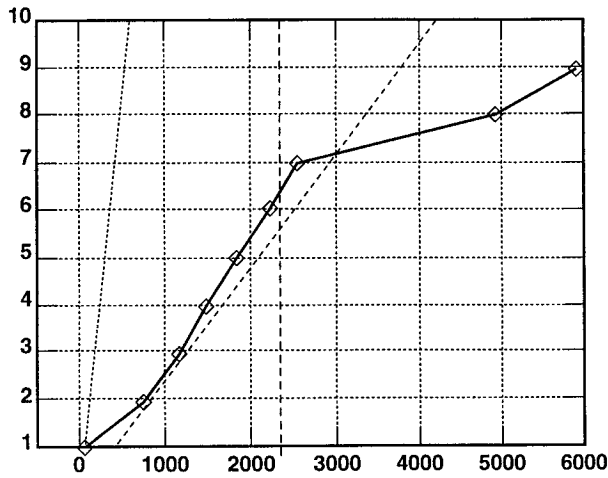


Figure 4. STA arrival rate graph.

MinT restriction limits. The steep line is the five nautical mile minimum separation limit. As aircraft arrive at feeder fix *TOMSN* they must be separated by at least five nautical miles, which corresponds to 60 seconds for jets which arrive at a speed of approximately 300 knots. The shallow line corresponds to a separation of 35 nautical miles. It is unlikely that TMCs issue restrictions of greater than 35 nautical miles between aircraft, for an aircraft can typically complete one revolution of a holding pattern in the time it takes to fly 35 nautical miles.

Thus the two straight lines represent MinT restriction bounds between minimum separation and holding. The ETA arrival rate curve for *TOMSN*_A shows that seven aircraft are projected to arrive at *TOMSN* during the scheduling period. The results of a MinT restriction of 30 nautical miles on the stream cause the seventh aircraft in the stream to arrive at *TOMSN* after the 2400 second limit (fig. 4). Note that the scheduled arrival time of the second aircraft in the stream remains the same as before the restrictions (figs. 3 and 4). This is because the scheduler does not “speed up” aircraft, as mentioned earlier. A restriction of 30 nautical miles delays the second through the seventh aircraft enough to reduce the traffic count into the TRACON by one over the scheduling period.

The arrival rate graph carries more information than do the ETA density or ETA integral. However, for automated scheduling, a parameter must be used to predict traffic development. The ETA integral seems to be the best choice, as it can distinguish between patterns (I-III) in figure 2. However, it is not clear that traffic with pattern (II) requires greater workload

in maintaining a given separation than traffic with pattern (III), for (III) can serve as an indicator that this traffic is likely to require greater work load in the future if something is not done with the traffic now. ETA density rates pattern (III) higher than pattern (II), something which can be useful in determining that restrictions put into effect now should not overburden a controller who could need to separate traffic later. For the purposes of analysis in this report, the ETA integral is used to sort the streams, but “traffic density” is used as a generic name for the metric used to distinguish between streams.

After sorting all streams by traffic density, the scheduling process begins with the lowest density stream by determining, as previously described, the maximum number of aircraft, N_1^{max} , which can be scheduled to enter the TRACON between t_0 and t_f . If this count is less than some minimum scheduling count, N_{min} , where

$$N_{min} \approx 5\%N_{acc} \quad (14)$$

then proceed to the next stream. That is, a stream must have at least N_{min} aircraft to be included in the restriction process. The value can be set by the TMC, and has been set to five percent of the acceptance count as a default. If the stream’s MinT was set by the TMC, continue on to the next stream. Otherwise proceed with the first stream as follows.

Determine the unrestricted traffic ratio, R_1 , for this stream, equation (10), multiply this ratio by N_{des} , and truncate to get the desired traffic count, N_1^{des} .

$$N_1^{des} = \lfloor R_1 N_{des} \rfloor \quad (15)$$

If this truncated value is greater than or equal to N_1^{max} , leave the stream unrestricted. Otherwise, add minimum separation increments to the stream separation (typically this is an increment of 5 nautical miles) and count the traffic resulting from the new schedule. Continue to increase the restrictions until the scheduled traffic count, N_1 , is equal to or has dropped below N_1^{des} , at which point the MinT is acceptable (conservative) for this stream. Subtracting N_1 from N_1^{max} yields the traffic reduction, N_1^{red} , due to restrictions for the first stream

$$N_1^{red} = N_1^{max} - N_1 \quad (16)$$

Subtracting N_1 from N_1^{des} results in the number of overly restricted aircraft, N_1^{res} , for this stream,

$$N_1^{res} = N_1^{des} - N_1 \quad (17)$$

Subtracting N_1^{red} from N_{un} results in the number of aircraft, N'_{MinT} , which enter the TRACON with the first stream restricted and the other streams unrestricted. If N'_{MinT} is below the desired count, N_{des} , enough restrictions have been imposed and we move on to the refinement scheduler. If N'_{MinT} still exceeds N_{des} , restrict the next stream (that which is more dense). This continues until all streams have been checked, or the scheduled count is below the desired count, N_{des} ,

$$N_j^{red} \equiv N_j^{max} - N_j \quad (18)$$

$$N_{red} = \sum_{j=1}^{Sres} N_j^{red} \quad (19)$$

$$N_j^{res} \equiv N_j^{des} - N_j \quad (20)$$

$$N_{res} = \sum_{j=1}^{Sres} N_j^{res} \quad (21)$$

$$N'_{MinT} = N_{un} - N_{red} \quad (22)$$

$$\leq N_{des} \quad (23)$$

where $Sres$ is the number of streams restricted to assure that N'_{MinT} is less than or equal to N_{des} . It is worth mentioning that after having cycled through all the streams, the scheduled count can still exceed the acceptance count. This can indicate one of several causes. Causes can be that the TMC restrictions were too low, or the traffic is arriving at the minimum scheduling rate, N_{min} , over many streams, or the desired traffic count is too far below the current count to be achieved without issuing holding restrictions (putting aircraft into holding patterns). The maximum restriction used by this scheduler is 35 MinT. Any greater restrictions are considered to be holding restrictions. Whatever the causes, the TMC is expected to alter the scheduling constraints before expecting the scheduler to develop more meaningful results. The more likely scenario is that the traffic is too restricted and the refinement algorithm is used to increase N'_{MinT} .

REFINEMENT SOLUTION

The refinement algorithm tries to remove some restrictions to increase N'_{MinT} , while keeping the traffic count into the TRACON at or below N_{des} . Beginning

with the most dense stream, remove one increment of restriction; if the restriction is greater than 5 nautical miles, count the resulting traffic, N'_S . Add this additional traffic, N_S^{inc} , to N'_{MinT} to form a new scheduled count N_{MinT} where

$$N_S^{inc} = N'_S - N_S \quad (24)$$

If N_{MinT} is still equal to or below N_{des} , schedule the stream with this lower MinT value. Otherwise, keep the previous value. In either case, continue to the next stream and perform similar calculations.

$$N_j^{inc} = N'_j - N_j \quad (25)$$

$$N_{MinT}^{incj} \equiv N_{MinT} + N_j^{inc} \quad (26)$$

$$N_{MinT} = N'_{MinT} + \sum_{j=1}^S \begin{cases} N_{S-j+1}^{inc}, & \text{if } N_{MinT}^{incj} \leq N_{des} \\ 0, & \text{otherwise} \end{cases} \quad (27)$$

This is done for all streams for the following reason. If there is a great difference in traffic count coming in through different streams, then reducing restrictions from a heavy stream can result in a lot of additional traffic coming through that stream, resulting in a total count which exceeds the desired count. If we were to stop here, we miss the opportunity of reducing restrictions on a lighter stream which would only increase the traffic count slightly, thus getting closer to the actual desired count, without exceeding it. It is worth noting that for this process of refinement, we have begun with the heaviest stream. This is again due to the fact that restrictions on the heavy streams require more effort than restrictions on the light streams, so reducing restrictions equates to reducing the work load, and possibly increasing the efficiency of the traffic flow.

RESULTS

To facilitate further research into the details of MinT scheduling, a low fidelity air traffic simulator has been developed in C++. This simulator has been used to run traffic simulations which were based on random number generation for aircraft ETAs and it has been used to read in data files from real traffic. Although work continues on refining the simulator, useful information about the effectiveness of the MinT logic has already been gained. It turns out that if there is a "heavy

side rush," which is to say that a few streams contain most of the traffic expected to enter the TRACON, then MinT developed by the scheduler seem quite reasonable. Problems arise, however, when there are only a few aircraft per stream, but there are many streams. For example, Denver International airport can have 16 streams of traffic. If each stream has three aircraft over a thirty minute interval, and the TRACON is accepting aircraft at the rate of 44 aircraft per 30 minute interval, it is not clear how to place restrictions on the streams to keep four aircraft from entering the TRACON. If the traffic is already well spread out on each stream, then three aircraft per thirty minutes could mean as much as 15 minutes, or 75 miles separation between aircraft in a stream, based on ETAs. Although an unlikely scenario, it does seem possible, and demonstrates that low density traffic on many streams can pose a scheduling problem. The larger the time range over which a solution is derived, the greater the potential is for deriving restrictions which seem excessive. Thus the average spacing of traffic in a stream over an hour may be 50 or 60 miles, although 20 minutes from now a pack of aircraft are estimated to arrive one minute apart. The scheduler updates as often as possible to be able to refine solutions based on actual traffic development.

Figures 5-8 depict ETA and STA rate graphs, respectively, for all traffic simulated to be flying in the Denver Center using new Standard Arrival Routes for Denver International Airport. The rate graphs are snapshots of projected traffic. Although at first glance the rate graphs for all traffic may appear arcane, there are useful properties of the traffic which are readily apparent from the graph. For example, we can very quickly determine how many aircraft are in each stream over the sampling time by reading the total aircraft count for each stream.

For example, from figure 6 we see that *Powdr_BC* has 14 aircraft estimated to arrive over the total sampling period, and *Ramms_A* has 11 aircraft projected to arrive over the sampling period. Also, we can very quickly get an estimate of where the traffic is most dense, as depicted by the slope of the arrival curves. Therefore, traffic arriving from the western streams remains fairly dense during the scheduling period from 0 to 2400 seconds, with the exception of *Tomsn_BC* and *Powdr_A*. Traffic density on the eastern streams is low until about 1800 seconds. From 1800 to about 3000 seconds we detect a surge in traffic density on the Eastern streams, depicted by the steeper slopes of

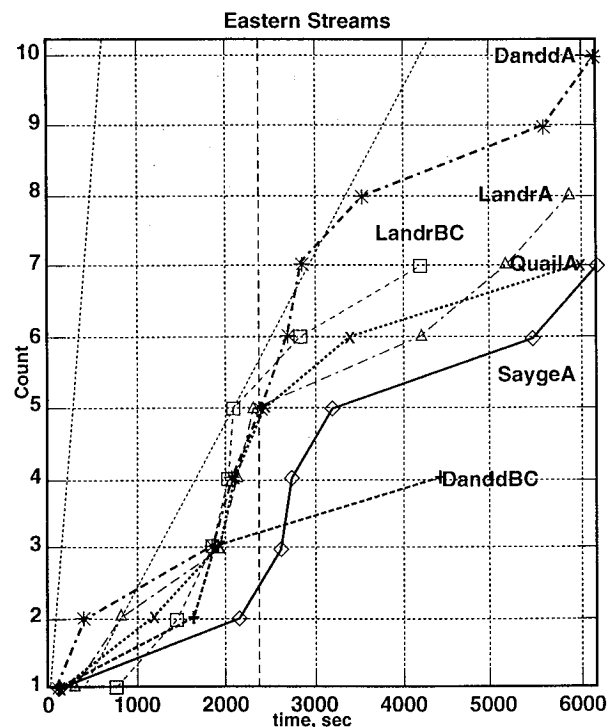


Figure 5. DIA Eastern ETA arrival rate graph.

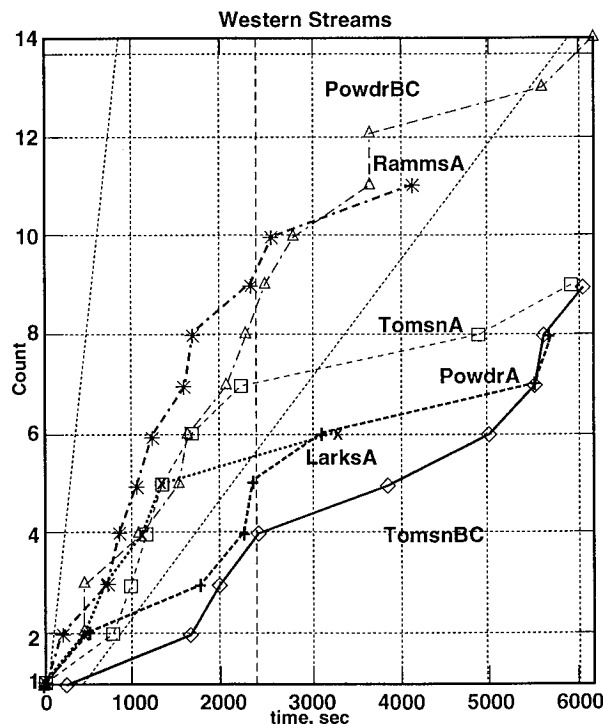


Figure 6. DIA Western ETA arrival rate graph.

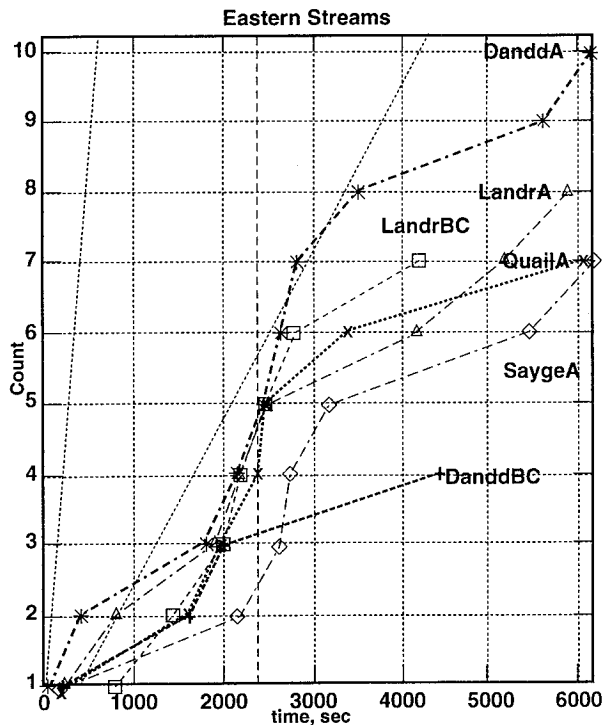


Figure 7. DIA Eastern STA arrival rate graph.

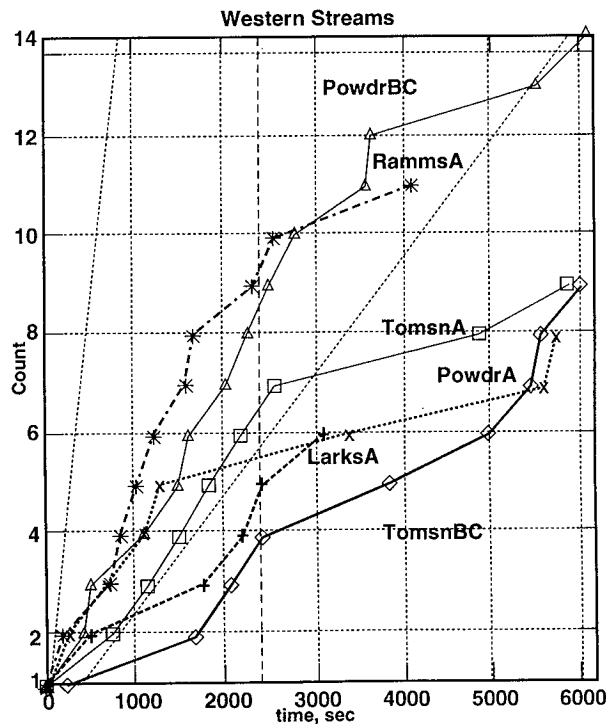


Figure 8. DIA Western STA arrival rate graph.

these streams in figure 5. Over the entire sampling period, the area under the ETA arrival rate curves, which relates to the ETA integral, is greater for *Powdr_BC* and *Ramms_A* than it is for the other curves, indicating that these two streams contribute most to the projected arrival rush of traffic. Finally, although difficult to reproduce in a static image of the arrival rate graphs, when one toggles between colored images of the ETA and STA arrival rate graphs in a graphical display on a computer screen, even subtle changes in the scheduled traffic are apparent and inform the analyst about possible effects of a scheduling plan. For example, toggling quickly shows that the fifth aircraft from *Powdr_A* and the seventh aircraft from *Tomsn_A* are delayed to arrive after the scheduling period, evidenced here by comparing the respective ETA and STA arrival rate curves in figures 6 and 8. Likewise, as evidenced by comparing figures 5 with 7, the fifth aircraft in *Landr_A* and *Landr_BC* and the fourth aircraft in *Quail_A* are delayed outside the scheduling period. The algorithm delayed five aircraft from arriving within the scheduling period, a requirement that meets the scheduling objective which was used for this simulation.

Table 1 shows restriction results from the scheduler attempting to reduce the traffic count from 61 to 56 aircraft over the 2400 second scheduling period in a simulation of traffic flying into Denver International Airport. The scheduler provides a solution which

Table 1. Scheduling results for DIA

Stream	ETA count	STA count	MinT (nmile)	Traffic density
Sayge BC	0	0	5	0
Quail BC	0	0	5	0
Rams BC	0	0	5	0
Larks BC	0	0	5	0
Sayge A	2	2	5	2874
Tomsn BC	3	3	35	4229
Dandd BC	3	3	35	4536
Landr BC	5	4	25	5461
Quail A	4	4	35	5567
Landr A	5	4	25	6429
Powdr A	5	4	15	6857
Dandd A	5	4	25	7301
Tomsn A	7	6	30	10199
Larks A	5	5	5	10492
Powdr BC	8	8	5	11557
Rams A	9	9	5	14121

meets the desired traffic reduction, and as can be seen from table 1, the reduction is achieved without restricting the three high density streams. The table listing is in ascending order of traffic density, as measured by the ETA integral, and thus represents the order in which restrictions were placed on the streams to meet the scheduling objective. From equation (14) we realize that traffic arriving from the first five streams in table 1 was not included for restrictions. To preserve the desired ratios according to equation (15), the traffic counts on each stream were to be reduced by only a fraction of an aircraft, then truncated. Thus, the scheduler was requested to introduce restrictions for each stream, beginning with *Tomsn_BC*, to delay one aircraft from arriving within the scheduling period, until five aircraft had been delayed outside this period. Note that the scheduler has developed restrictions which did not affect the three streams with greatest traffic density, thus presumably reducing controller workload. The solution is also equitable in attempting to preserve the estimated traffic ratios for each stream. Note that the restrictions on streams *Tomsn_BC*, *Dandd_BC*, and *Quail_A* are unnecessary, as the traffic in these streams is already sufficiently separated, and restrictions on these streams have no effect on the desired traffic count.

Finally, table 2 shows how many aircraft were scheduled to enter the TRACON compared with the acceptance rates requested for several simulations of the new and old airspace configurations for Denver. As one can see the scheduler does well in restricting the traffic to the desired count. The table also shows how quickly the traffic requires restrictions of 35 nautical miles on all streams to reduce the traffic count to the desired count. The algorithm has met the objective of distributing traffic reductions which reduces the traffic count to the desired count in most cases, and the solutions met the objective of reducing controller workload, as measured by ETA integral, while maintaining a sense of equitable delay distribution. However, as previously stated, it remains to be seen, through traffic simulations with TMCs, whether or not the assumptions herein meet the ultimate objective of providing an automation tool which effectively aids the TMC in his traffic restriction decision process.

Table 2. Aircraft counts for Denver

DIA start 61 ac		Stapleton start 28 ac	
Desired	Scheduled	Desired	Scheduled
60	60	27	26
59	59	26	26
58	58	25	25
57	57	24	24
56	56	23	24
55	55	22	22
54	54	21	22
53	53	Count of 20 = all ac holding	
52	52		
51	51		
Count of 50 = all ac holding			

CONCLUSIONS

A Miles-in-Trail (MinT) scheduling algorithm has been developed to aid a TMC in determining MinT restrictions on Center air traffic destined for arrival in a TRACON. The algorithm is effective in determining restrictions which reduce the predicted traffic count to a desired count. Two traffic identifiers have been created to evaluate traffic based on aircraft ETAs—the ETA density and ETA integral. These are used as measures which relate to controller workload in executing a scheduling plan. A graphical technique for monitoring the traffic conditions has also been developed. The technique is referred to as an arrival rate graph which allows one to quickly determine traffic count from each stream over a scheduling period, and traffic arrival rate from a stream to a destination. These identifiers were used in traffic simulations using the scheduling algorithm here presented. The results provided by the algorithm should reduce controller work load, as measured by the ETA integral. The restrictions are equitable in distributing aircraft delay over the streams, when one accounts for the fact that the restriction technique must affect an entire stream of traffic. Results from simulations run with the algorithm are favorable when most of the traffic is developed to enter through a few streams.

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13. ABSTRACT (Maximum 200 words) This paper presents an algorithm which can be used for scheduling arrival air traffic in an Air Route Traffic Control Center (ARTCC or Center) entering a Terminal Radar Approach Control (TRACON) Facility. The algorithm aids a Traffic Management Coordinator (TMC) in deciding how to restrict traffic while the traffic expected to arrive in the TRACON exceeds the TRACON capacity. The restrictions employed fall under the category of <i>Miles-in-Trail</i> —one of two principal traffic separation techniques used in scheduling arrival traffic. The algorithm calculates aircraft separations for each stream of aircraft destined to the TRACON. The calculations depend upon TRACON characteristics, TMC preferences, and other parameters adapted to the specific needs of scheduling traffic in a Center. Some preliminary results of traffic simulations scheduled by this algorithm are presented, and conclusions are drawn as to the effectiveness of using this algorithm in different traffic scenarios.				
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